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(54) Title: LASER DIRECT WRITING OF PLANAR LIGHTWAVE CIRCUITS
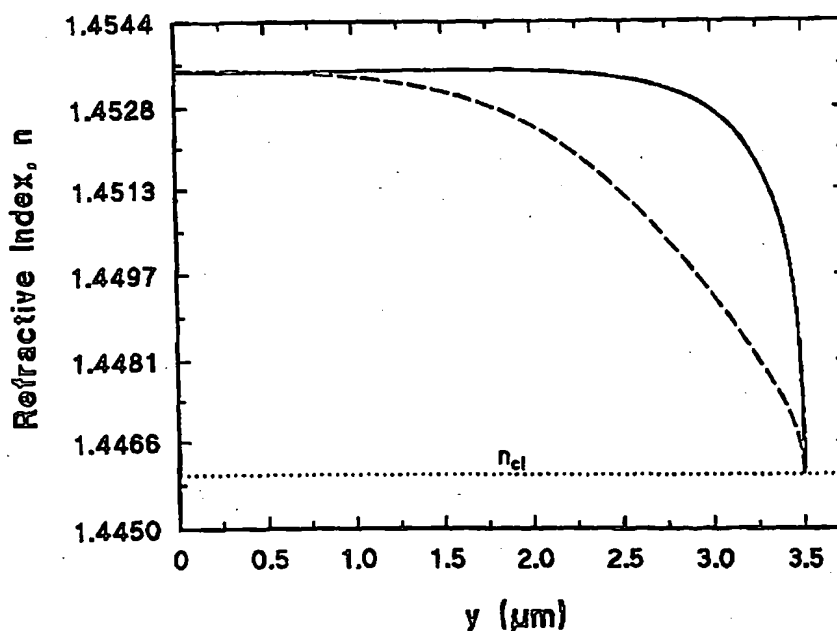
(57) Abstract

A laser beam with an annular or ring shaped intensity distribution, such as a TEM_{01}^* beam, is scanned across the surface of a photosensitive thin film to directly produce changes of refractive index in selected regions of the film. This method is suitable for producing channel waveguides for planar lightwave circuits, where the refractive index profile (solid curve) of such a waveguide is more uniform than the prior art refractive index profile (dashed curve) produced by a TEM_{00} laser beam, and has a reduced bend loss.

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LASER DIRECT WRITING OF PLANAR LIGHTWAVE CIRCUITS

Field Of The Invention

This invention relates to the production of planar lightwave circuits (PLC's). More
5 particularly, the invention relates to a method for defining the light wave circuit or
components of the circuit by direct photoinduced changes in refractive index of a thin film
forming the basis of the PLC.

Background Art

10 There is an increasing demand for planar lightwave circuits for advanced optical
communications networks, optical sensing and also as the basis of other photonic devices,
such as high frequency signal processors for use in military and other applications.

The basis of most PLC's is a trilayer of optically transparent thin films deposited on a
15 substrate of generally silicon or silica as shown in Figure 1. The central, or core layer 1 of
the sandwich structure normally has higher refractive index n_{co} than the refractive index n_{cl}
of outer cladding layers 2, 3, and this simple system is known as a planar waveguide. Light
injected into the core layer undergoes total internal reflection at both core/cladding boundaries
4, 5 and is confined in this transverse dimension, resulting in 1-dimensional light guidance.
20 However as a consequence of the constant refractive index in the plane of the film total
internal reflection is not possible, and light spreads or diffracts laterally in the guiding layer.
To impart useful functionality to a planar waveguide, 2-dimensional light guidance is
required, and planar diffraction must be overcome by introducing local changes in the core
layer refractive index. The light guides so formed are known as channel waveguides, the
25 basic elements of PLC'S, and the final product is a planar lightwave circuit which can exhibit
a wide range of optical functions. An example of a simple device is a concatenated Y-junction
splitter where the signals from a single input channel are split evenly into a larger number of
output channels independent of wavelength.

30 Currently, there are several classes of materials and processing methods which can be used
to produce planar waveguides. These include silica glass (using plasma enhanced chemical

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vapour deposition: PECVD, or flame hydrolysis: FHD); organically modified silicate glasses

(ORMOSILs) and plastics produced via wet chemical synthesis and spin coating; and III-V semiconductors produced by MOCVD or MBE growth.

5

The waveguides in the PLC are defined by structuring or patterning of the refractive index in the plane of the film. In the microelectronics industry, the standard patterning technique is known as mask photolithography. The first step in this process is to deposit an additional thin film of photo resist onto the planar waveguide core, usually by spin coating. The photo

10 resist film is then preferentially exposed to a broadband extended UV source through an amplitude mask such that a photochemical reaction is initiated below the high transmission areas of the mask. The photochemical reaction changes the solubility of the photo resist enabling it to be removed by agitation in a suitable solvent. Depending on whether negative or positive tone resist is used, the irradiated regions will remain or be removed respectively.

15 The photo resist pattern may then be transferred to the waveguide core layer by removing core material from the unwanted regions by a process such as reactive ion etching. Removal of the remaining resist and over cladding with a low refractive index film completes the standard processing of the PLC. Two dimensional waveguiding is therefore achieved through selective removal of the high index core material.

20

As an alternative to the photo resist technology, materials such as plastics, ormosils and some glasses can allow refractive index patterning to be achieved without the use of an additional photo resist layer. In this class of materials, direct exposure generally to UV radiation initiates a photochemical reaction that raises the refractive index of the core material, enabling

25 channel waveguides to be formed. The materials are generically described as photosensitive. The use of mask photolithography on these films therefore results in the production of PLC'S without the requirement for the deposition of an additional photo resist layer or any reactive ion etching or wet development.

30 The production of a suitable mask is however costly and time consuming and, particularly in the prototyping stage, limits the number of device designs that can be tested. Recently it has

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been demonstrated that the requirement for a mask can be eliminated by using the laser direct writing (LDW) technique. This is described in M. Svalgaard, 'Direct writing of planar waveguide power splitters and directional couplers using a focused ultraviolet laser beam', *Electronics Letters*, Vol. 33, No. 20, pp. 1694-1695, 1997. In contrast to standard mask

5 photolithography, in the LDW process the photosensitive planar waveguiding film is accurately traversed under a focused laser beam to locally expose the material and directly delineate the channel waveguides without the use of a mask. The LDW process is very versatile and permits a wider range of structures than is generally possible by exposure through a mask. For example, using a mask the exposure will be uniform across the whole

10 wafer, and hence the refractive index change obtained cannot vary from one part of the waveguide structure to the next. Using LDW, on the other hand, permits the exposure, and hence the induced change of the refractive index, to be adjusted even over short distances permitting a wider range of waveguide structures to be written. Furthermore, the LDW process permits the waveguide pattern to be changed from wafer to wafer because the

15 generated pattern can be under direct software control.

As with mask photolithography, depending on the waveguide material used, the laser induced photochemical reaction can either directly induce a refractive index change in the waveguiding material without further processing, the material system can be locally exposed and then

20 subjected to wet development, or a secondary layer of photo resist may be used and the photo resist pattern transferred to the waveguiding core layer. Therefore depending on the laser source, the process is applicable to many different material systems e.g. glass, polymer, sol-gel, $Ti:LiNbO_3$. In addition, the use of high power lasers and/or different laser wavelengths can access photosensitive mechanisms that cannot be attained with mask photolithography.

25

In general the refractive index, n, of a photosensitive material is dependent on it's exposure, F, to electromagnetic radiation, and as shown in Figure 2 the material response function, $n(F)$, typically exhibits a saturation behaviour up to a maximum exposure, F_{sat}. A plan view of the laser writing process is shown in Figure 3, where we consider delineation of a channel

30 waveguide of width $2a$ in the z direction. For a laser irradiance distribution, $I(y,z)$, the lateral exposure of the material in the y direction, $F(y)$, is given by;

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$$F(y) = \frac{1}{v} \int_{-\sqrt{a(a-y)}}^{\sqrt{a(a-y)}} I(y,z)dz \qquad\qquad (1)$$

where v is the writing velocity. The lateral exposure, $F(y)$, for a truncated (beam waist, $w=a$) TEM$_{00}$ beam with irradiance distribution $I(y,z)=I_{00}\exp(-2(y^2+z^2)/w^2)$, is shown by the dashed line in Figure 4. Clearly the exposure is peaked around $y=0$. For optimum use of

5   the available refractive index change the maximum lateral exposure, F_{max} should equal the material saturation exposure, F_{sat}. Taking into account the material response $n(F)$, the corresponding refractive index distribution $n(y)$ also shows a maximum at $y=0$ as shown by the dashed line in Figure 5. Laser direct write systems so far have employed the focusing or imaging of weakly truncated Gaussian (TEM$_{00}$) beams, and operating under this scenario

10 therefore produce channel waveguides with laterally graded refractive index profiles. Indeed, graded thickness profiles are often observed in wet developed polymer waveguides. This is described in L. Eldada, L. W. Shacklette, R. A. Norwood and J. T. Yardley, 'Next-generation polymer photonic devices', *Sol-Gel and Polymer Photonic Devices*, SPIE Vol. CR68, pp. 207-227, 1997. Graded index profiles have some disadvantages when factors such

15 as bend loss and form birefringence are taken into account.

Disclosure Of The Invention

It is an object of this invention to provide a method of directly producing photoinduced changes in refractive index that provides a more uniform lateral refractive index distribution.

20

Accordingly, in one broad aspect this invention provides a method of directly producing photoinduced changes in refractive index in selected regions of a photosensitive thin film by selectively scanning a laser beam across the surface of the film, characterised in that the laser

25 beam impinging the film has an annular substantially circularly symmetric irradiation intensity distribution.

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As used herein the term annular intensity distribution includes any transverse intensity distribution that has a very low or zero intensity in a central region and a surrounding region of higher intensity. The radial intensity distribution within the surrounding region can be substantially uniform or may vary. This type of intensity distribution is sometimes

5 referred to as a "doughnut type" distribution. Such a distribution is achieved, for example, by a $TEM_{01}*$ laser beam although higher order modes can also produce an intensity distribution having similar characteristics. The $TEM_{01}*$ is a hybrid mode consisting of a superposition of TEM_{01} and TEM_{10} with a constant phase difference of $\pm \pi/2$. The radial intensity distribution in a $TEM_{01}*$ beam is given by

10

$$I(y,z) = I_{01} \left(\frac{y^2}{w_1^2} + \frac{z^2}{w_2^2} \right) \exp\left(-2\left(\frac{y^2}{w_1^2} + \frac{z^2}{w_2^2} \right) \right) \qquad (2)$$

where w_1 and w_2 are beam waists and $w_1 \approx w_2$

In the preferred form of the invention a $TEM_{01}*$ laser beam is used. The beam, for example, can be generated from a Gaussian laser beam by a diffracting phase mask technique as

15 described in N. R. Heckenberg, R. McDuff, C. P. Smith and A. G. White, 'Generation of optical phase singularities by computer-generated holograms', *Optics Letters*, Vol. 17, No. 3, pp. 221-223, 1992. A $TEM_{01}*$ beam can also be produced directly from a laser by suitable modification to the cavity optics.

20 The use of a beam with an annular or doughnut type irradiance distribution results in a lateral exposure $F(y)$ that produces a more uniform lateral refractive index distribution, $n(y)$. This is achieved because $I(y,z)$ is modified such that the contribution to the integral in equation (1) near $y=0$ is reduced. In addition, to avoid introducing a preferential writing direction the focused beam must remain substantially circularly symmetric.

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The invention will be further explained, by way of example only, with reference to the accompanying.

Brief Description of the Drawings

5   Figure 1 is a schematic illustration of a planar waveguide;

Figure 2 illustrates the typical refraction index response of a photosensitive medium as a function of exposure to electromagnetic radiation;

Figure 3 is a schematic planar view of a laser circuit writing process used in the method of this invention;

10   Figure 4 illustrates the lateral exposure function of $TEM_{01}*$ (solid line) and TEM_{00} (dashed line) for equal maximum exposure writing scenarios;

Figure 5 illustrates the lateral refraction index distribution for $TEM_{01}*$ (solid line) and TEM_{00} (dashed line) for equal maximum exposure writing scenarios; and

Figure 6 illustrates bend loss for $TEM_{01}*$(solid line) and TEM_{00} (dashed line) written 15 waveguides of equal spot size and maximum exposure.

Best Mode For Carrying Out The Invention

The method of this invention utilises a laser direct write (LDW) technique in which a focussed $TEM_{01}*$ laser beam is used. The LDW technique is known to those skilled in the art and will 20 not be described in detail.

The $TEM_{01}*$ 'doughnut mode' has an irradiance distribution which exhibits zero intensity at the beam centre. The maximum exposure is constrained to be equal to the material saturation exposure and results in the lateral refractive index distribution as shown in Figure 5. The 25 laser writing with a $TEM_{01}*$ beam gives a larger photoinduced refractive index change in the outer regions of the beam than that obtained with a TEM_{00} counterpart of equal F_{max} Furthermore, the change of index is more uniform over the waveguide region. These features impart desirable properties to the photoinduced waveguides. The more uniform lateral refractive index profile generated by the 'doughnut' mode beam, has several technical 30 advantages when compared with LDW systems using Gaussian modes.

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A practical consideration related to the general use of all PLC's is that it is usual for the input and output ports to be connected to the rest of the optical network with silica optical fibres. For maximum optical power transfer from the fibre to the channel waveguides comprising the PLC, the spot size and symmetry of the channel guided mode must equal that of the circularly

5   symmetric fibre guided mode. For a given material system with a specified F_{sat} this excitation efficiency criterion determines the dimensions of the channel waveguides. If the channel waveguides produced using either TEM_{00} or TEM_{01}^* mode LDW must have mode sizes that are matched to those of a typical communications fibre, and the same maximum exposure of the photosensitive layer is used for both TEM_{00} and TEM_{01}^* LDW, then a larger diameter

10 writing beam is required in the TEM_{00} case. This is because, as shown in Figure 5, the photoinduced refractive index changes are low in the outer regions of the beam for TEM_{00} exposure. The waveguide must therefore be made physically wider to pull the optical field out to match the fibre mode field size.

15 In the weak guidance regime, the mode effective index can be approximated as a weighted average of the refractive index distribution, $n(x,y)$, seen by the mode, i.e.

$$N_{eff}^2 \approx \frac{\int\int n^2(x,y)\psi^2(x,y)dxdy}{\int\int \psi^2(x,y)dxdy} \qquad (3)$$

where $\psi(x,y)$ is the mode function. Evaluating equation (3) for both the TEM_{00} and TEM_{01}^*

20 cases gives a lower effective index value in the TEM_{00} case. Expressing this in terms of the normalized effective index, B, defined as;

$$B = \frac{N_{ef}^2 - n_{cl}^2}{n_{co}^2 - n_{cl}^2} \qquad (4)$$

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where n_{cl} is the cladding refractive index and n_{co} is the maximum photoinduced refractive index, gives a B value typically 20% higher in the $TEM_{01}*$ case. The channel guided light is, therefore, more strongly confined in $TEM_{01}*$ written waveguides, under the constraints of maximum excitation efficiency and $F_{max} = F_{sat}$. The stronger confinement imparts significant

5   technical advantages for the $TEM_{01}*$ written waveguides.

Useful functionality is only achieved in a PLC if the channel waveguides are routed in curved paths from one region of the optical chip to another, and this requires bending of the waveguides in the plane of the film. When a channel waveguide is bent, an amount of power,

10 L, is inescapably lost to radiation per unit length of bend. L is strongly dependent upon the radius of curvature of the bend; the tighter the bend, the greater the bend loss. For a constant radius, the magnitude of L is directly related to how strongly the guided mode is confined. Channel waveguides produced by $TEM_{01}*$ LDW, therefore, exhibit significantly reduced bend loss compared to channel waveguides formed by TEM_{00} LDW. This feature is illustrated in

15 Figure 6. The minimum bend radius (for 0.1dB/cm bend loss) permissible for a $TEM_{01}*$ written guide may be as small as ~75% the value of that possible using waveguides written by TEM_{00} mode beams. This significantly impacts the device density on the planar waveguide typically increasing by a factor of 1.8 the number of devices that can be written on a given area of the optical "chip".

20

In addition, the index profiles generated through $TEM_{01}*$ LDW result in channel waveguides with form birefringence reduced by typically a factor of 2 relative to TEM_{00} written guides.

Variations in laser intensity or writing velocity (and therefore exposure) during the laser direct

25 writing process will result in fluctuations in the effective index of the optical guided mode. In the case of $TEM_{01}*$ LDW these fluctuations produce a comparatively smaller change (by typically a factor of 2) in effective index and hence the required tolerance on exposure is increased.

30 The emergence of wavelength division multiplexing (WDM) as the method of choice for expanding the bandwidth of existing optical networks means that spectrally selective elements

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are often required in PLC's. In many cases the required PLC functionality is acquired by photo defining Bragg reflection phase gratings into the existing PLC channel waveguides. In this case the TEM_{01}* and TEM_{00} channel waveguide exposure conditions would be determined such that the maximum exposure did not completely saturate the available photoinduced

5 refractive index change i.e. $F_{max}=0.7F_{sat}$ for example. For efficient Bragg reflection to occur the photoinduced phase grating should be written uniformly across the waveguide, requiring a uniform index distribution, $n(y)$, in the channel waveguide. Clearly channel waveguides produced by TEM_{01}* LDW satisfy this criterion better than channel waveguides formed by TEM_{00} LDW.

10

It will be apparent that the application of the method of this invention to direct writing of channel optical waveguides provides a number of advantages over previously known techniques. These include:

-     a near-uniform lateral refractive index profile.

15 -   reduced bend loss in the laser written optical waveguides.

-     reduction in the effect of exposure fluctuations on waveguide parameters.

-     reduction of form birefringence in laser written optical waveguides.

-     the ability to write laterally uniform Bragg graftings by post photodefinition.

-     the availability of photoinduced tuning of the waveguide effective index.

20 -   the ability to produce optical waveguides with X-junctions requiring double the single mode core refractive index in the crossing region.

-     uniform exposure of photosensitive thin films.

The foregoing describes only some of the variations within the scope of this invention and

25 further modification can be made without departing from the scope of the invention.

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The Claims

1.   A method of directly producing photoinduced changes in refractive index in
selected regions of a photosensitive thin film by selectively scanning a laser beam across the
surface of the film, characterized in that the laser beam impinging the film has an annular
substantially circularly symmetric irradiation intensity distribution.

2.   A method as claimed in claim 1 wherein the radial intensity distribution across
the annulus is substantially uniform.

3.   A method as claimed in claim 1 wherein the annular distribution is provided
by a TEM_{01}^* laser beam.

4.   A method as claimed in claim 1 including the step of producing the TEM_{01}^*
laser from a Gaussian laser beam using a diffracting phase mask technique.

5.   A method as claimed in any one of claims 1 and 4 wherein the film is a planar
waveguide and including the step of scanning said laser beam so that said photoinduced
changes produce one or more channel waveguides in the photosensitive film to create a planar
lightwave circuit.

6.   A method as claimed in claim 5 wherein said waveguides have modes sizes
substantially matched to those of a typical communications optical fibre.

7.   A method as claimed in claim 5 or claim 6 wherein at least one waveguide
includes a curved path.

8.   A method as claimed in any one of claims 5 to 7 including the step of not
completely saturating the available photoinduced refractive index change to provide for
subsequent selective photoinduced refractive index changes to a portion of or portions of the

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waveguide.

9.   A method as claimed in claim 8 including the step of producing said subsequent selective changes to define spectrally selective elements.
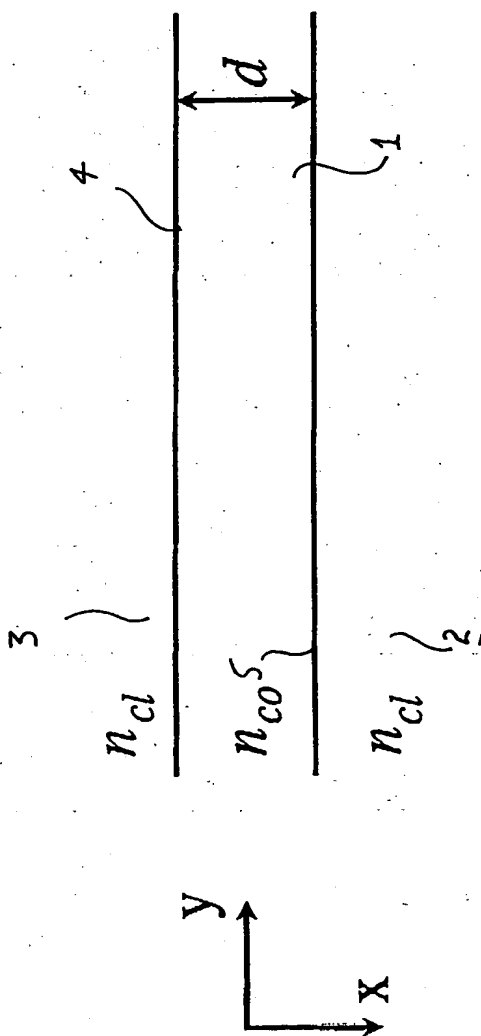
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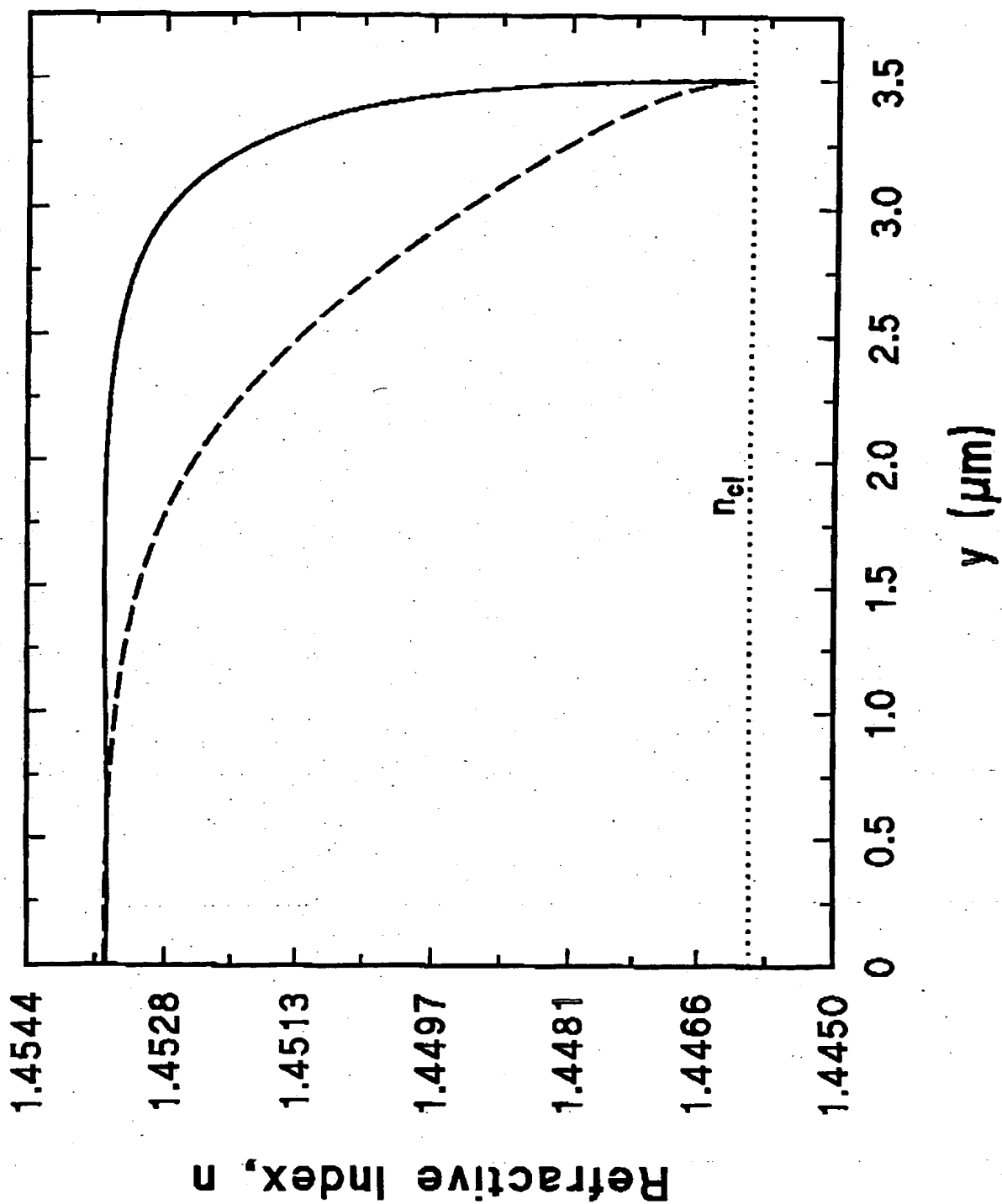
FIGURE 1

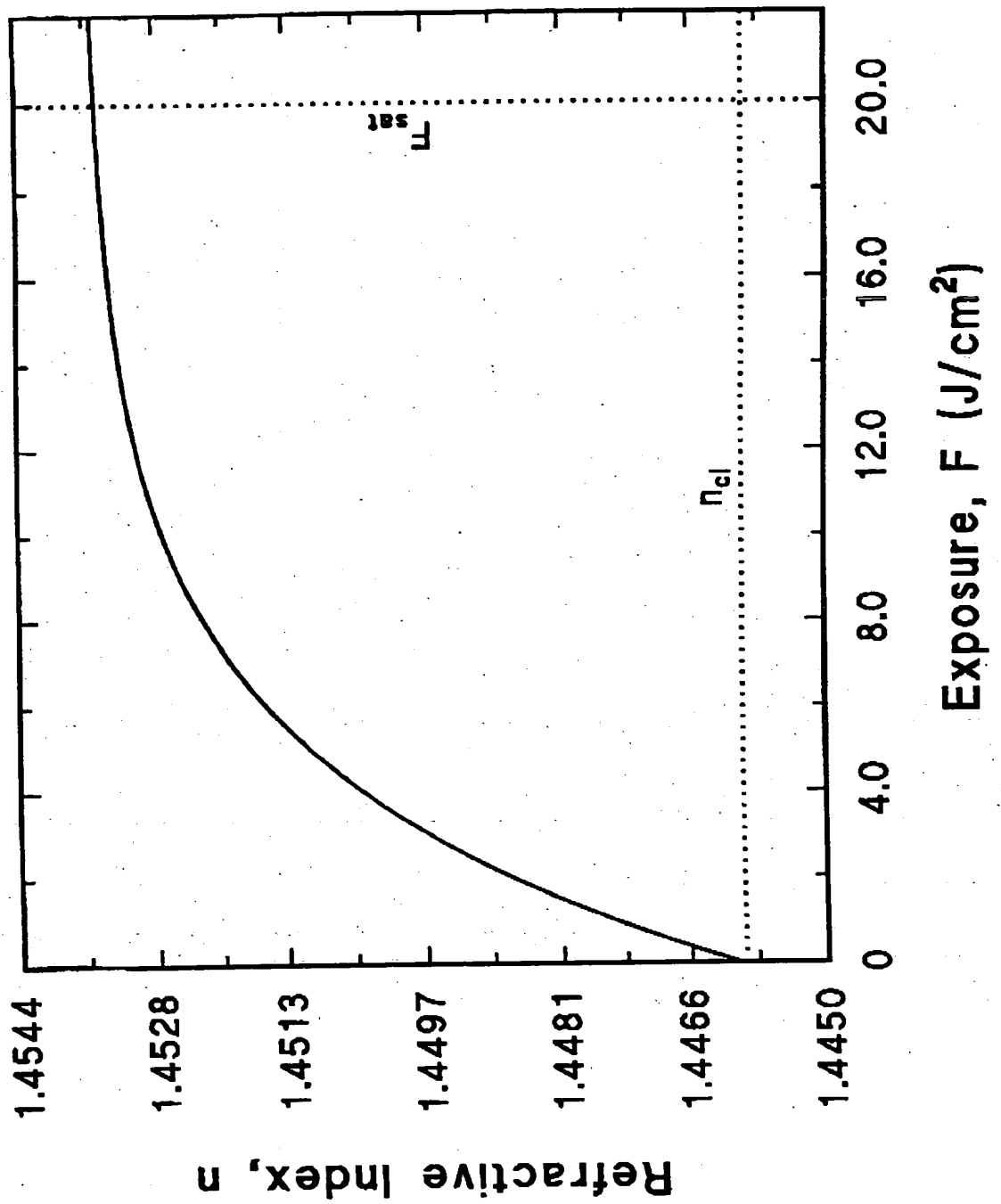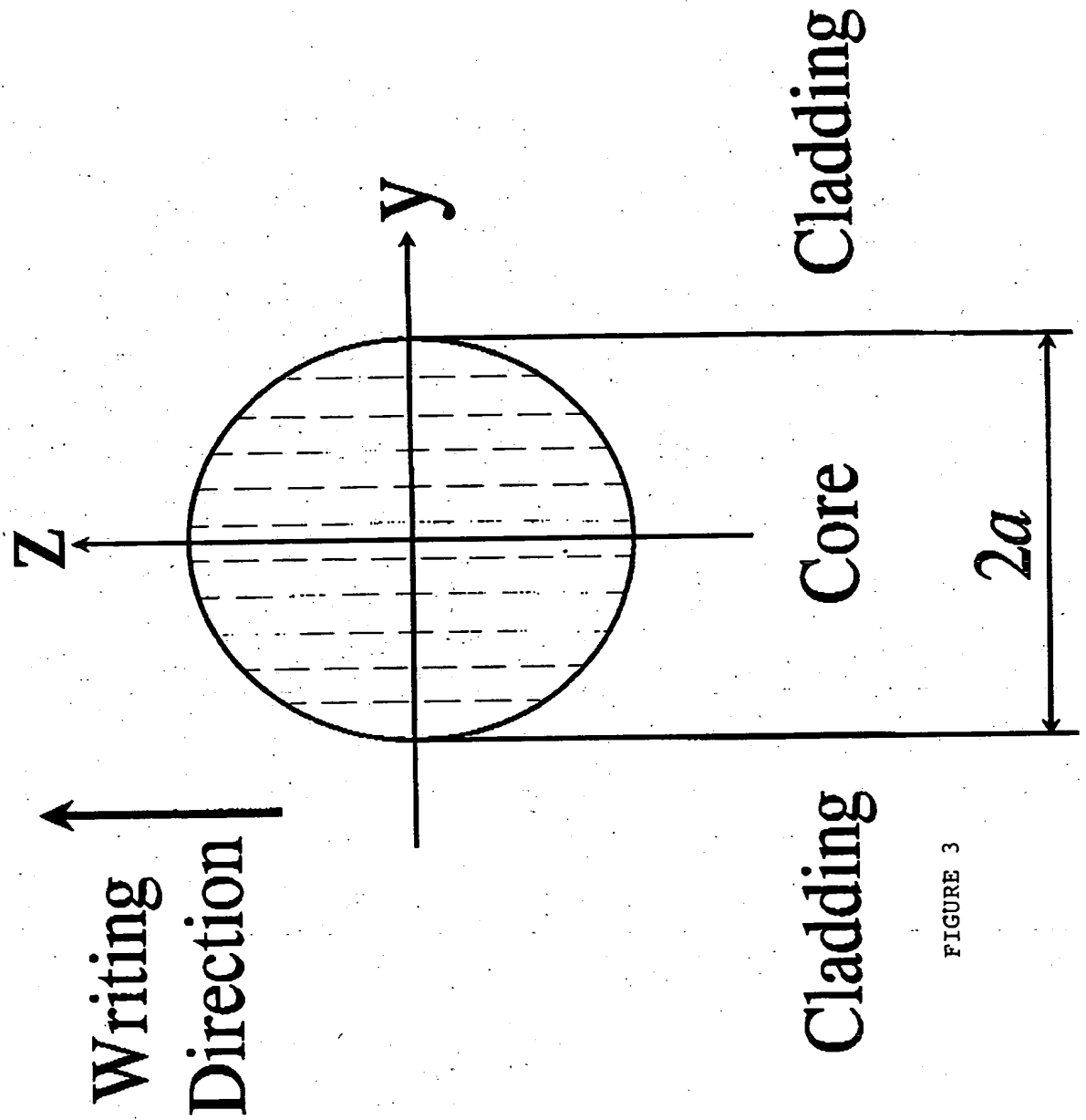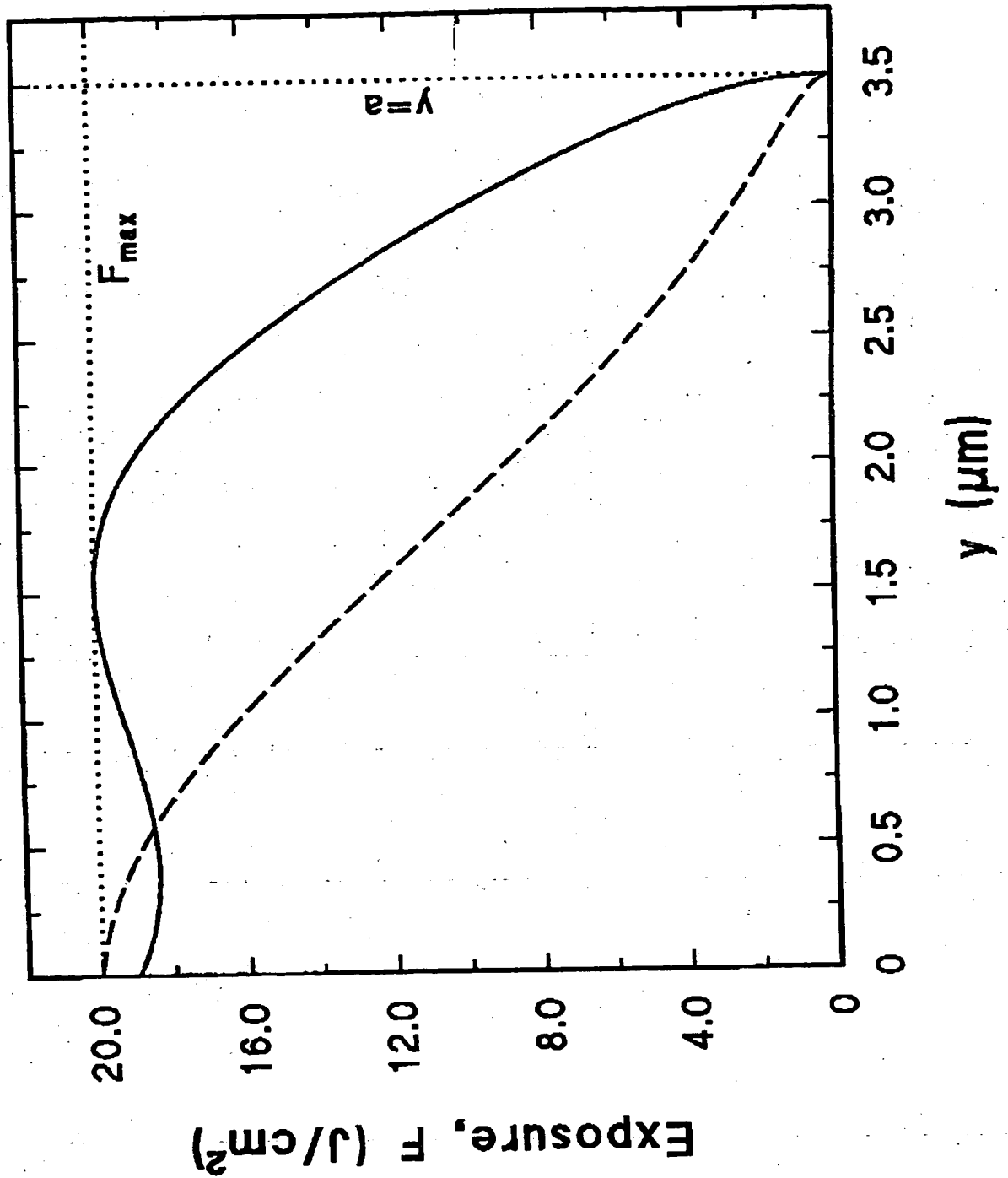FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5
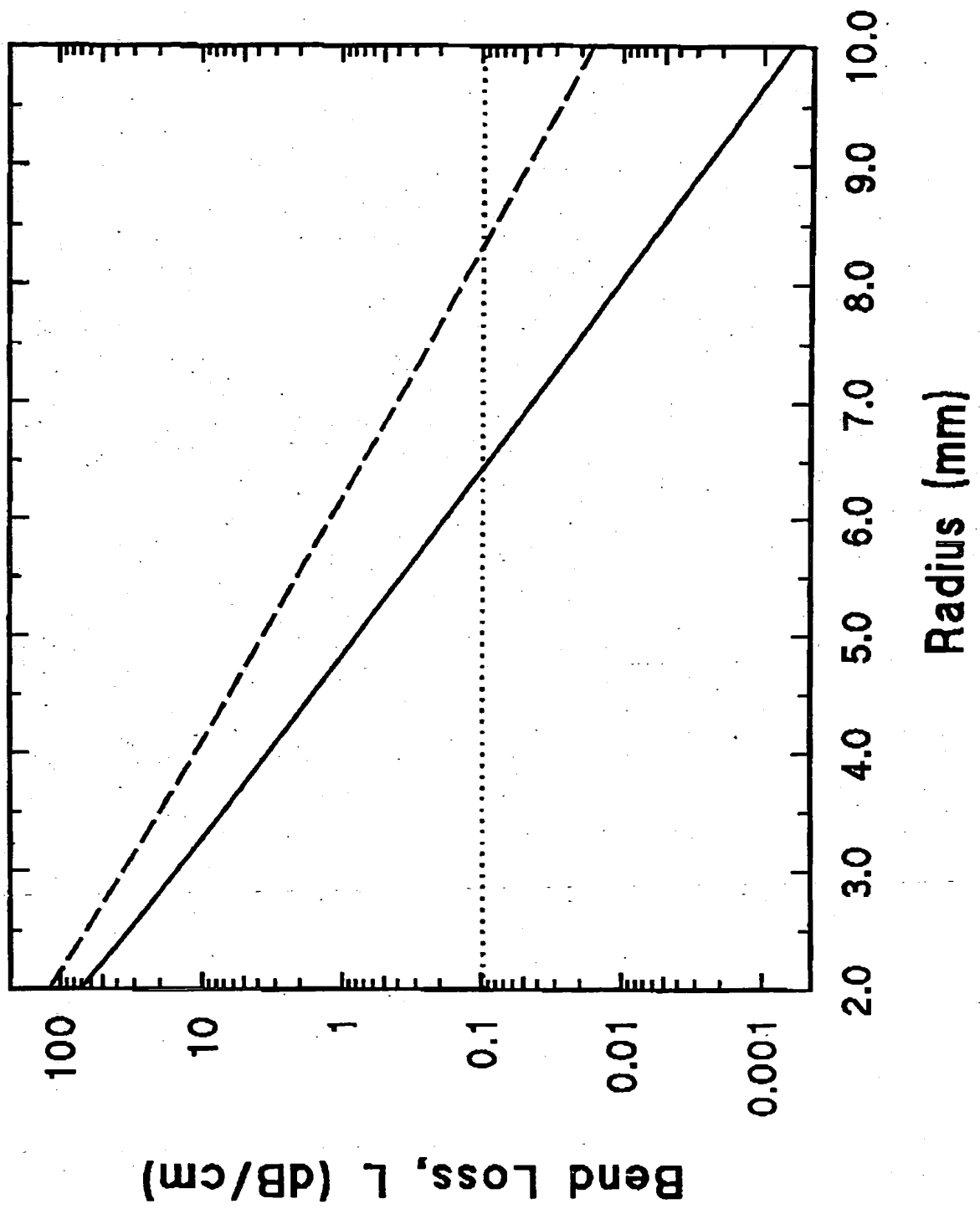
FIGURE 6

A.	CLASSIFICATION OF SUBJECT MATTER

Int Cl^6:   G02B 6/13

According to International Patent Classification (IPC) or to both national classification and IPC

B.	FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC: G02B 6/-, G03F 7/20, 7/22

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WPAT, JAPIO, INSPEC

C.	DOCUMENTS CONSIDERED TO BE RELEVANT	
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P, X	ACOFT'98 Proceedings: 23rd Australian Conference on Optical Fibre Technology, 5-8 July, 1998 (IREE Society, Sydney), R. Charters et al., "Laser Direct Writing of Polymeric PLC's using a TEM$_{01}$* Beam", pages 37-40 Whole document	1-9
A	US 5629805 A (FUKUZAWA) 13 May 1997 Column 2 lines 33-52, Figure 5	1
A	Patent Abstracts of Japan, M-971, page 22, JP 2-52724 A (OSAKA PREFECTURE(1)) 22 February 1990 Abstract	1

☐ Further documents are listed in the continuation of Box C	☒ See patent family annex

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 July 1999	− 2 AUG 1999
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200 WODEN ACT 2606 AUSTRALIA Facsimile No.: (02) 6285 3929	Authorized officer MICHAEL HALL Telephone No.: (02) 6283 2474

INTERNATIONAL SEARCH REPORT
Information on patent family members

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member	
US	5628805	JP	7142369

END OF ANNEX